OPTICAL SWITCHING DEVICE USING COUPLED WAVEGUIDES IN PHASE MATCHING STRUCTURE

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Introduction:

Guided-wave electrooptic or nonlinear switching element exhibits fast switching required for optical communication system in the future. Switching principle that uses coupling between orthogonal polarization waveguide modes (TM and TE) has been proposed[1]. Recently noble structure was adapted to nonlinear optic wavelength conversion device to separate converted light from other input light[2]. Nonlinear directional coupler using Kerr effect[3] and second harmonic generation (SHG) [4,5] has been proposed. In this report, we analyze the device structures based on coupling equations for phase matching coupled waveguides and show that many types of device configuration are possible[6]. Polarization independent switching or filtering devices are obtained using polarization mode conversion. New nonlinear optical directional coupler related to cascaded nonlineary[5, 7], using SFG (sum frequency generation) or DFG (difference frequency generation), is described.

Normal modes in phase matching structure:

The coupled waveguides under phase matching condition can be described by following coupled-wave equations. We consider two-waveguide system.

$$dA_1/dz = j\gamma_1 B_1 + j\delta A_1 + jkA_2$$
$$dA_2/dz = j\gamma_2 B_2 + j\delta A_2 + jkA_1$$
$$dB_1/dz = j\gamma_1 A_1 - j\delta B_1 + jkB_2$$
$$dB_2/dz = j\gamma_2 A_2 - j\delta B_2 + jkB_1 \qquad (1)$$

where A_i and B_i are A and B modes in ith waveguide. The coefficient γ denotes coupling between A and B modes, δ the detuning form the phase matching condition and k the coupling between two waveguides. For a coupling between polarization modes, the coupling coefficient γ is generated by off-diagonal electrooptic effect.

When $-\gamma_2 = \gamma_1 = \gamma$, equation 1 can be simplified by using new modes $A_i + B_i = C_{ei}$ and $A_i \quad B_i = $

C_{oi}. Combination of A and B depends on the form of the coupling coefficients γ_1 and γ_2.

$$dC_{e1}/dz=j\gamma C_{e1}+j\delta C_{o1}+jkC_{e2}$$
$$dC_{e2}/dz=-j\gamma C_{e2}+j\delta C_{o2}+jkC_{e1}$$
$$dC_{o1}/dz=-j\gamma C_{o1}+j\delta C_{e1}+jkC_{o2}$$
$$dC_{o2}/dz=j\gamma C_{o2}+j\delta C_{e2}+jkC_{o1} \qquad (2)$$

Next, we consider the two-waveguide system under phase-matched condition ($\delta=0$). In the phase-matched condition, it is known from Eq. 2 that C_{ei} and C_{oi} propagate separately with no coupling between them. Modes C_{e1} and C_{e2} (C_{o1} and C_{o2}) propagated along the two waveguides (No. 1 and 2) interact through coupling coefficient k between waveguides. In the case of the orthogonal polarization modes A and B, the new modes C_o and C_e corresponds to polarization modes tilted 45 degrees against A and B respectively (Fig. 1). The propagation constant difference between modes C_o and C_e is 2γ, when these modes are propagated in each waveguide at the phase-matched condition and there is no coupling between waveguides (k=0). Since A= $(C_o + C_e)/2$ and B= $(C_o - C_e)/2$ the full mode conversion is attained when the phase between modes C_o and C_e becomes π.

Possible device configurations:
Coupling equations (Eq. 2) show that directional coupler and reversed $\Delta\beta$ can be implemented at phased matched condition. The coupling coefficient between modes A and B on two waveguides should be in opposite polarity for switching. The consideration leads to configurations shown in Fig. 2a and 2b. The grating structures on two waveguides for phase matching are shifted π to each other. For the polarization conversion device, the finger electrode (or SAW) generates the grating structure. Polarization independent switching is attained in the phase matching condition, since both C_o and C_e modes are switched simultaneously.

When the two waveguides are separated so that each waveguide can be considered as independent waveguides (k=0) and in phased matched conditions, the accumulated phase difference between modes propagated in different waveuides can be controlled by mode coupling coefficient γ as can be derived from Eq. 2. Mach-Zehnder type switch can be constructed connecting 3dB couplers placed at the input and output with phase-matched mode conversion waveguides with large gap between them (Fig. 2c). In the simplest case, a Y-branch is used as 3dB coupler. The input Y-branch excites symmetric mode at the beginning of the mode conversion waveguide. When there is no mode conversion, the symmetric mode is fed into the Y-branch. The on state is attained. When mode conversion takes place so that a mode is converted to another mode $2\gamma L=\pi$ at mode conversion waveguide length L, the phase between

two waveguide modes at the output coupler entrance becomes reversed becoming an asymmetric mode. The off state is attained. Polarization independent switching is attained in the phase matching condition, since both C_o and C_e modes are switched simultaneously. The switch response of mode conversion Mach-Zhender interferometer is shown in Fig. 3.

Wavelength conversion device:

For a wavelength conversion, the coupling coefficient is a function of pump light and nonlinear optic coefficient under constant pump power condition in which the depletion of the pump light is neglected. The power transfer between signal and converted lights occurs with no total power change. The coupling equations for the SFG are derived under this assumption from nonlinear coupling equations as

$$d(E_{a2} \pm r_a E_{a3})/dz = \pm jF_a[E_{a2}\exp(j\Delta_a z) \pm r_a E_{a3}\exp(-j\Delta_a z)] + jk(E_{b2} \pm r_a E_{b3})$$

$$d(E_{b2} \pm r_b E_{b3})/dz = \pm jF_b[E_{b2}\exp(j\Delta_b z) \pm r_b E_{b3}\exp(-j\Delta_b z)] + jk(E_{a2} \pm r_b E_{a3}) \qquad (3)$$

where E_{i1} is the pump light amplitude, E_{i2} the signal light amplitude and E_{i3} the converted (SFG) light amplitude in the ith waveguide respectively. Δ_i is the detuning from the phase matching condition in the ith waveguide taking quasi phase-matching (QPM) effect into account. The parameter k is the coupling coefficient between a and b waveguides, $r_i = [\omega_2 K_i * E_{i1} * /(\omega_3 K_i E_{i1})]^{1/2}$ and $F_i = [\omega_2 \omega_3 K_i * E_{i1} * K_i E_{i1}]^{1/2}$. K_i is the nonlinear coupling coefficient in ith waveguide and $\omega_{2,3}$ the light frequency. When $K_a = -K_b = K$ and under the phase matching condition $\Delta_i = 0$, Eq. 3 becomes the same as equation for directional coupler with F_i being the propagation constant difference between two waveguides. The composite field of signal and SFG lights behave like a field in each waveguide of the directional coupler. Controlling F_i by the pump light amplitude E_{i1} enables the switching function.

Similar equation is derived for DFG. An equation similar to Eq. 3 holds for entangled two-wavelength field of a light field and its complex conjugate.

Switching devices are possible similar to those shown in Fig. 2. Device with fast switching speed is expected using all-optical switching performed by controlling of the device with the pump light.

Conclusions:

In this report we have shown that directional coupler and Mach-Zhender type switching device can be implemented using mode or wavelength conversions under the phase-matching condition. Polarization independent switching or filtering devices are obtained using polarization mode conversion. Nonlinear optical directional coupler using SFG and DFG is described.

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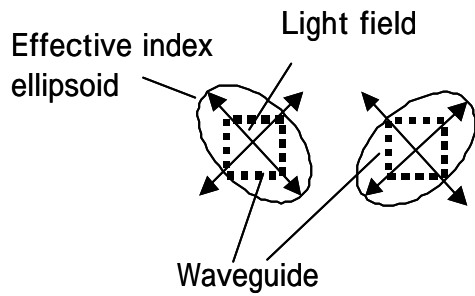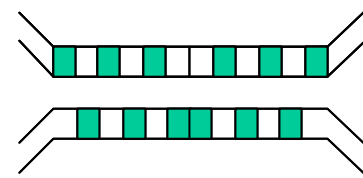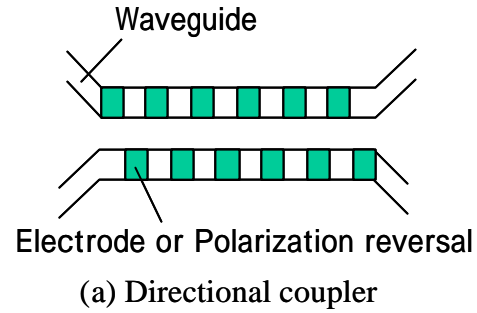
Fig. 1 Light polarization field at phase matching condition

(a) Directional coupler

(b) Reversed $\Delta\beta$

(c) Mach-Zhender interferometer
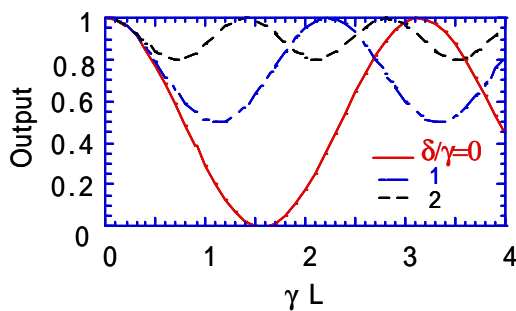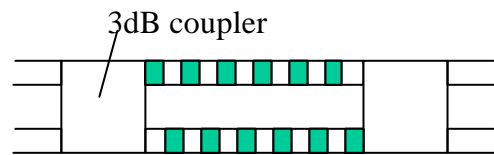
Fig. 2 Switching device configurations

Fig. 3 Switch response of mode conversion M-Z interferometer

(γ: mode coupling coefficient, δ: detuning from the phase matching)